

Large retrograde Centaurs: visitors from the Oort cloud?

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Abstract Among all the asteroid dynamical groups, Centaurs have the highest fraction of objects moving in retrograde orbits. The distribution in absolute magnitude, H , of known retrograde Centaurs with semi-major axes in the range 6–34 AU exhibits a remarkable trend: 10% have $H < 10$ mag, the rest have $H > 12$ mag. The largest objects, namely (342842) 2008 YB₃, 2011 MM₄ and 2013 LU₂₈, move in almost polar, very eccentric paths; their nodal points are currently located near perihelion and aphelion. In the group of retrograde Centaurs, they are obvious outliers both in terms of dynamics and size. Here, we show that these objects are also trapped in retrograde resonances that make them unstable. Asteroid 2013 LU₂₈, the largest, is a candidate transient co-orbital to Uranus and it may be a recent visitor from the trans-Neptunian region. Asteroids 342842 and 2011 MM₄ are temporarily submitted to various high-order retrograde resonances with the Jovian planets but 342842 may be ejected towards the trans-Neptunian region within the next few hundred kyr. Asteroid 2011 MM₄ is far more stable. Our analysis shows that the large retrograde Centaurs form an heterogeneous group that may include objects from various sources. Asteroid 2011 MM₄ could be a visitor from the Oort cloud but an origin in a relatively stable closer reservoir cannot be ruled out. Minor bodies like 2011 MM₄ may represent the remnants of the primordial planetesimals and signal the size threshold for catastrophic collisions in the early Solar System.

Keywords Celestial mechanics · Minor planets, asteroids: general · Minor planets, asteroids: individual: (342842) 2008 YB₃ · Minor planets, asteroids: individual: 2011 MM₄ · Minor planets, asteroids: individual: 2013 LU₂₈ · Planets and satellites: individual: Uranus

1 Introduction

In our planetary system, most objects go around the Sun following counterclockwise (prograde) orbits as viewed from above the north pole of our star. However, a large number of comets orbit the Sun clockwise (retrograde) and a substantial percentage of these objects have highly inclined orbits. They are believed to have their origin in the Oort cloud (see e.g. Duncan 2008), a vast and remote spherical reservoir of cometary material tens of thousands of astronomical units in diameter that completely surrounds the Solar System.

Out of 3265 objects currently classified by the Jet Propulsion Laboratory (JPL) Small-Body Database¹ as comets, 1918 move in retrograde orbits (58.7%). For long-period comets the retrograde fraction is 49.7%, for Halley-type comets is 35.7% and for Jupiter-family comets is 16.7%. In contrast, only 53 of the 641502 currently catalogued asteroids orbit the Sun clockwise (0.008%). For asteroids in the outer Solar System (catalogued as Centaurs or trans-Neptunian objects) the fraction of retrograde objects is 2.7% (48 out of 1804). Therefore, most retrograde asteroids have been found in the region of the giant planets and beyond. At 11.0% (30 out of 272 catalogued objects in the JPL Small-Body Database), Centaurs have the highest retrograde fraction among all the dynamical groups or asteroid families.

Centaurs are a transient asteroidal population whose orbits cross those of the outer planets (see e.g. Di Sisto and Brunini 2007). Most Centaurs may have their origin in the trans-Neptunian belt, some may have come from the Oort cloud. The main source of Centaurs remains to be discovered. They are probably an heterogeneous population with multiple sources (see e.g. Di

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¹<http://ssd.jpl.nasa.gov/sbdb.cgi>

Sisto et al. 2010), perhaps none being dominant (but see Horner and Lykawka 2010).

The most intriguing of the known Centaurs are those moving in retrograde orbits. The study of retrograde Centaurs, especially those following high inclination trajectories, may represent a rare opportunity to look at objects that have suffered little surface alteration over the age of the Solar System (Sheppard 2010). The three largest known (in terms of absolute magnitude, H) retrograde Centaurs are (342842) 2008 YB₃ ($H = 9.3$ mag), 2011 MM₄ ($H = 9.3$ mag) and 2013 LU₂₈ ($H = 8.1$ mag); they all move in near-polar orbits. Minor bodies following eccentric, high-inclination paths spend most of the time well beyond the plane of the Solar System and away from the destabilizing influence of the giant planets, although close encounters with these planets are still possible at the nodes.

Here, we show that, far from being just dynamical curiosities, the three largest retrograde Centaurs may be the key to identify the size threshold for catastrophic collisions in the early Solar System. On the other hand, they are also submitted to retrograde mean motion resonances that make them dynamically unstable, emphasizing the fact that these objects have not remained in their current orbits for long. This paper is organized as follows. In Sect. 2, we present a comparative statistical analysis of the properties of known prograde and retrograde Centaurs that reveals compelling reasons to single out the largest retrograde objects. The current dynamical status of these large retrograde Centaurs is studied in Sect. 3, where the numerical model used in our N -body simulations is also briefly discussed. In Sect. 4, we consider the implications of our results and in Sect. 5 we summarize our conclusions.

2 Retrograde Centaurs

Following Alexandersen et al. (2013), let us consider the group of minor bodies whose semi-major axes are between 6 and 34 AU. There are 266 such asteroids currently (as of 2014 May 5) in the JPL Small-Body Database. This number is slightly less than the total number of known Centaurs quoted above. Out of them, 236 (88.7%) follow prograde orbits and 30 (11.3%) follow retrograde orbits. Figure 1 shows the distribution in orbital parameter space and H of prograde (left-hand panels) and retrograde (right-hand panels) Centaurs. Even if the number of known retrograde Centaurs is small, it is highly improbable that the two Centaur populations have a common origin. The distribution in absolute magnitude, which is a proxy for size, clearly shows that retrograde Centaurs are unlikely to be the

result of gravitational scattering of originally prograde Centaurs, unless we assume that smaller objects are more efficiently scattered to become retrograde than larger ones (see the e - and i -panels) or that smaller retrograde objects are easier to identify than their prograde counterparts.

Most prograde orbits have eccentricities in the range 0.2–0.6 and relatively low inclinations, $<20^\circ$. The small but noticeable group of prograde orbits with inclination $\sim 63^\circ$ in Fig. 1 (left-hand panel) is consistent with predictions made by e.g. Gallardo (2006) on the existence of objects submitted to the Kozai resonance at that critical inclination. The relative excess of objects with argument of perihelion close to 0° or 180° could be due to observational bias because only objects with declinations $|\delta| < 24^\circ$ are observed (see de la Fuente Marcos and de la Fuente Marcos 2014).

The raw distribution in H of prograde orbits shows evidence of the so called divot or sudden decrease in numbers for $H \sim 9$ mag (or a diameter of nearly 100 km) as found by e.g. Shankman et al. (2013). This has been interpreted by those authors as the relic signature of the size distribution of the primordial planetesimal population, with the larger objects being the remnants. A divot in the size distribution of trans-Neptunian objects was predicted by Fraser (2009) using the results of collisional evolution calculations. A lack of objects in the size range 1–20 km was also anticipated by Charnoz and Morbidelli (2007) for minor bodies in the scattered disk and the Oort cloud. This feature had been previously identified and confirmed observationally for the size range 25–60 km by Bernstein et al. (2004), Fuentes and Holman (2008), and Fraser and Kavelaars (2009). This break in the size distribution may signal the onset of collisional evolution. Schlichting et al. (2013) consider that, for trans-Neptunian objects, the observed size distribution above a radius of ~ 30 km is primordial. They also found that there is a significant deficit of bodies with size ~ 10 km and a strong excess of bodies of nearly 2 km in radius; this excess leaves a permanent signature in the size distribution of these objects that is still clearly observable after 4.5 Gyr of collisional evolution. Fraser et al. (2014) have found that the observed size distributions are difficult to explain within the currently accepted standard model of planetesimal formation.

The distribution in H for retrograde orbits in Fig. 1 (left-hand panel) exhibits a most unusual behaviour. There are only three objects (10%) with $H < 10$ mag: (342842) 2008 YB₃ ($H = 9.3$ mag), 2011 MM₄ ($H = 9.3$ mag) and 2013 LU₂₈ ($H = 8.1$ mag). The rest have $H > 12$ mag (73.3% have $H > 14$ mag). Although the number of known retrograde Centaurs is small, this

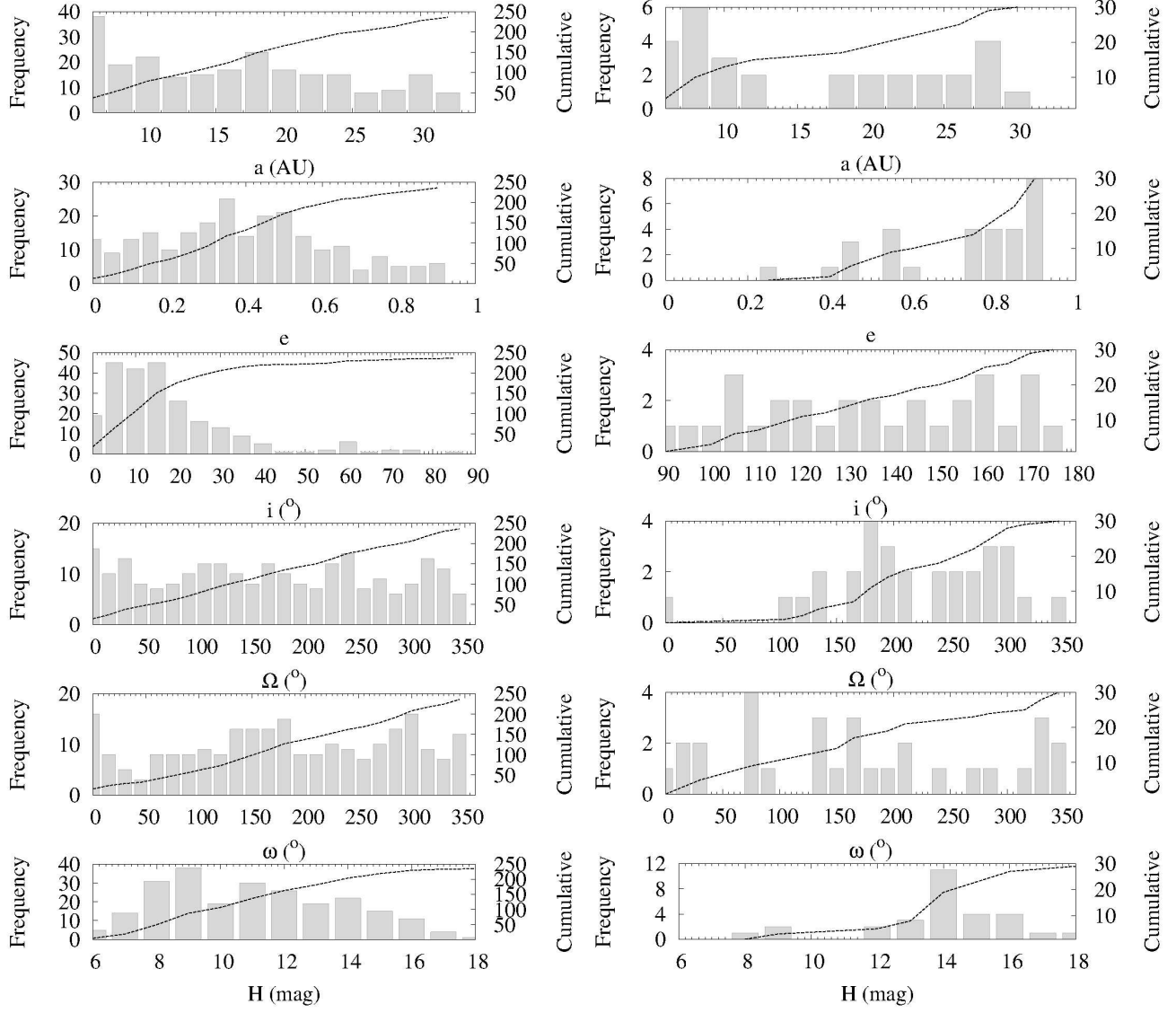


Fig. 1 Distributions in semi-major axis, a , eccentricity, e , inclination, i , longitude of the ascending node, Ω , argument of perihelion, ω , and absolute magnitude, H , of observed Centaurs following prograde (left-hand panels) and retrograde orbits (right-hand panels).

result can be seen as a dramatic confirmation of the existence of a break in the size distribution as predicted by e.g. Fraser (2009). There is an obvious deficit of objects with H in the range 10–14 mag although they must be significantly easier to detect, if they do indeed exist, than fainter objects of a size below 10 km. Although the available sample is far from complete and likely biased, it should not be biased in favour of 1-km objects against those in the size range 10–100 km. The scarcity of intermediate-size objects must be real and it may have a collisional, dynamical or even primordial origin (or a combination of the three). In principle, and following Fraser (2009), Schlichting et al. (2013) or Shankman et al. (2013), some or all the large retrograde Centaurs may represent a remnant population of primordial planetesimals.

In addition, the distribution in H of retrograde Centaurs suggests that at least two distinct populations of rather different dynamical origin are present. In support of this interpretation, Fig. 2 (see also Fig. 3) shows the distribution in the (a, e) plane of both groups and comets in the same semi-major axis range: the three largest retrograde Centaurs clearly stand out (bottom panel). The brightest (largest) objects also appear to be dynamically different. The distribution of semi-major axes and eccentricities of retrograde objects with $H > 12$ resembles that of members of the detached or scattered disk populations (Levison and Duncan 1997; Gomes 2011). In terms of the size of their members, these trans-Neptunian populations appear to be of collisional origin and, dynamically, they may have reached their current state after suffering strong gravitational perturbations. The surprising abundance of retrograde minor bodies at $H \sim 14$ mag may signal a high density of objects with size ~ 1 km as predicted by Fraser (2009) or, more recently, Belton (2014).

It may be argued that we unfoundedly invoked the observed decrease in the number of prograde Centaurs at magnitude $H \sim 9$ to implicitly justify the division into two groups ($H < 10$ mag and $H > 10$ mag) in Fig. 2. However, such concern is completely unjustified as Fig. 2 clearly shows. It is rather obvious from the figure that the three largest retrograde Centaurs are clear dynamical outliers because they have the largest perihelia. Out of the three largest retrograde Centaurs, only 342842 is a relatively well-studied object (Sheppard 2010; Pinilla-Alonso et al. 2013; Bauer et al. 2013). But, what is special or unique about these objects? Both 342842 and 2013 LU₂₈ can suffer close encounters with Jupiter; 2011 MM₄ may be considerably more stable.

Brasser et al. (2012) and Volk and Malhotra (2013) have found that retrograde or very high inclination Centaurs cannot have evolved from the trans-Neptunian

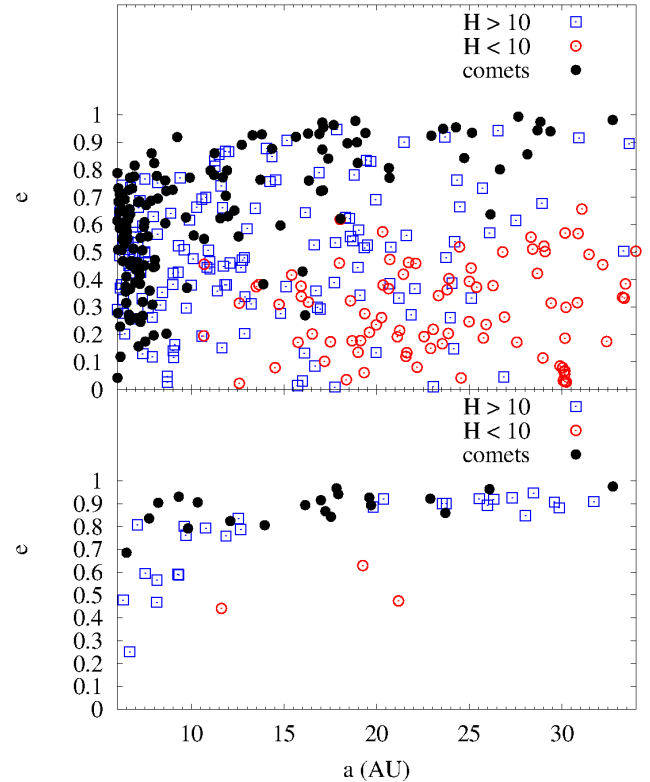


Fig. 2 The distribution in the (a, e) plane of prograde (top panel) and retrograde (bottom panel) Centaurs and comets with semi-major axes in the range 6–34 AU. There are 145 prograde and 20 retrograde comets in that semi-major axis range. See also Fig. 3. The three largest retrograde Centaurs, namely (342842) 2008 YB₃, 2011 MM₄ and 2013 LU₂₈, are clear dynamical outliers; they have the largest perihelia.

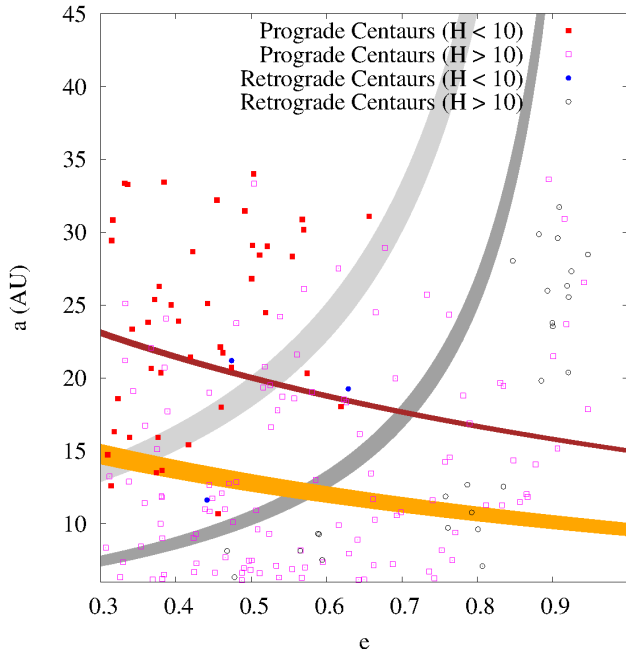


Fig. 3 Positions of the group of present-day Centaurs discussed in Sect. 2 in the (e, a) plane. The dark gray area represents the eccentricity/semi-major axis combination with periapsis between the perihelion and aphelion of Jupiter, the light gray area shows the equivalent parameter domain if Saturn is considered instead of Jupiter. The orange area corresponds to the (e, a) combination with apoapsis between the perihelion and aphelion of Uranus and the brown area shows the counterpart for Neptune.

belt due to close encounters with the Jovian planets. Instead, they favour a source in the Oort cloud for these objects. In the Solar System, near-polar orbits are almost dynamically frozen in time and, potentially, they could be stable for hundreds of Myr. This is particularly true if the nodes of the orbits of the objects remain relatively far from the paths of the planets. However, if the objects following these unusual trajectories are also submitted to mean motion resonances, their dynamical stability could be compromised even if they do not undergo close encounters with planetary bodies because they may experience chaotic diffusion.

Morais and Namouni (2013a) have brought to the attention of the astronomical community that minor bodies following retrograde orbits around the Sun may also be trapped in a mean motion resonance with a planet. The same authors have identified several asteroids currently moving in retrograde resonance with Jupiter and Saturn (Morais and Namouni 2013b). This discovery is of considerable practical interest because of its potential impact on our understanding of the early stages of the evolution of the Solar System and also on the dynamics of transient populations like the Centaurs. Are the largest retrograde Centaurs perhaps submitted to retrograde mean motion resonances with the giant planets?

3 Dynamical evolution of large resonant retrograde Centaurs

The dynamics of resonant retrograde minor bodies has been studied by Morais and Namouni (2013a, 2013b). For an object in retrograde resonance with a planet that moves in a prograde orbit, the resonant argument can be written as $\sigma = q\lambda - p\lambda_P - (q + p - 2k)\varpi + 2k\Omega$, where λ and λ_P are the mean longitudes of the retrograde object and the prograde planet, respectively, ϖ is the longitude of perihelion of the retrograde object, $\varpi = \omega - \Omega$, Ω is the longitude of the ascending node and ω is the argument of perihelion. The mean longitude of a prograde object is given by $M + \Omega + \omega$, where M is the mean anomaly, but the one for a retrograde object is written as $M + \omega - \Omega$. The numbers p , q and k are integers with $p + q \geq 2k$. If the two objects are in resonance, $T/T_P = p/q$, where T and T_P are the orbital periods of the retrograde object and the prograde planet, respectively. If, over a given period of time, the resonant argument, σ , can take any value in the range $0-360^\circ$, then it circulates but if it exhibits oscillations (symmetric or asymmetric) around a certain value (usually 0° or 180°), then we say that it librates. If the resonant argument librates, then the

Table 1 Heliocentric ecliptic Keplerian orbital elements of large retrograde Centaurs (342842) 2008 YB₃, 2011 MM₄ and 2013 LU₂₈. Values include the 1σ uncertainty (Epoch = JD2456800.5, 2014-May-23.0; J2000.0 ecliptic and equinox. Data for 2013 LU₂₈ are referred to epoch 2456455.5, 2013-Jun-12.0. Source: JPL Small-Body Database.)

		(342842) 2008 YB ₃	2011 MM ₄	2013 LU ₂₈
Semi-major axis, a (AU)	=	11.61769±0.00007	21.183±0.011	19±18
Eccentricity, e	=	0.440962±0.000003	0.4739±0.0004	0.6±0.5
Inclination, i (°)	=	105.02980±0.00002	100.4457±0.0002	117±6
Longitude of the ascending node, Ω (°)	=	112.498683±0.000010	282.6016±0.0005	266±7
Argument of perihelion, ω (°)	=	330.70350±0.00009	7.07±0.02	179±38
Mean anomaly, M (°)	=	29.3043±0.0003	34.75±0.03	298±142
Perihelion, q (AU)	=	6.494734±0.000003	11.144±0.004	7±4
Aphelion, Q (AU)	=	16.74064±0.00011	31.22±0.02	31±30
Absolute magnitude, H (mag)	=	9.3	9.3	8.1

object is trapped in a $p:q$ retrograde (or $p:-q$) mean motion resonance with the planet. Retrograde resonances are weaker than their prograde counterparts (Morais and Namouni 2013a, 2013b).

In this work, the orbital evolution of the three largest retrograde Centaurs is computed using the Hermite integration scheme described by Makino (1991) and implemented by Aarseth (2003). The standard version of this N -body sequential code is publicly available from the IoA web site². Our numerical simulations include the gravitational perturbations of the eight major planets, the Moon, the barycentre of the Pluto-Charon system and the three largest asteroids (dwarf planet (1) Ceres, (2) Pallas and (4) Vesta). Initial positions and velocities are based on the DE405 planetary orbital ephemerides (Standish 1998) referred to the barycentre of the Solar System. Together with the orbital elements, they have been obtained from the JPL on-line Solar System data service³ (Giorgini et al. 1996). In the integrations, the relative error in the total energy was always as low as 3.0×10^{-15} or lower after a simulated time of 1 Myr. The corresponding error in the total angular momentum is several orders of magnitude smaller. Further details on the physical model and the validation of the code can be found in de la Fuente Marcos and de la Fuente Marcos (2012a). Besides the calculations performed using the nominal orbits as provided by the JPL Solar System data service, we have followed the evolution of 50 additional control orbits obtained from the nominal ones and the quoted uncertainties (see Table 1). Their orbital elements have been sampled from a six-dimensional Gaussian distribution around the nominal ones (within 3σ with the exception of 2013 LU₂₈). In all the figures, $t = 0$ coincides with the JD2456800.5 epoch unless explicitly stated. The

dynamical evolution of the objects is followed for ± 500 kyr.

Figures 4, 5 and 6 evidence that the overall orbital evolution of the three objects is rather different although all of them experience horizontal oscillations in the (e, a) plane as secular resonances modify e at constant a . These figures also show that, when ω is close to 0° or 180° , (342842) 2008 YB₃ can experience close encounters with Jupiter at perihelion and with Uranus at aphelion, 2011 MM₄ can encounter Saturn at perihelion and Neptune at aphelion, and 2013 LU₂₈ can find Jupiter at perihelion and Neptune at aphelion (see also Fig. 3). Encounters can only take place at the nodes of the orbit. For a retrograde orbit, the distance between the Sun and the nodes (Fig. 6, F-panels) is given by $r = a(1 - e^2)/(1 \pm e \cos \omega)$, where the ‘+’ sign denotes the descending node and the ‘-’ sign the ascending node. In the following, we explore the dynamics of these unusual objects in more detail.

3.1 (342842) 2008 YB₃

Asteroid (342842) 2008 YB₃ was discovered on 2008 December 18 by R. H. McNaught observing for the Siding Spring Survey with the 0.5-m Uppsala Schmidt (McNaught et al. 2008). When first observed, it had a V magnitude of 18.1. It was soon obvious that it follows a near-polar retrograde orbit characterized by $a = 11.62$ AU, $e = 0.44$ and $i = 105^\circ$ (see Table 1). Its orbit is well determined with 466 observations spanning a data-arc of 1856 d. It is relatively large with $H = 9.3$ mag or a diameter of 67 km for an albedo of 6.2%, although it is probably larger. Sheppard (2010) found moderately red colours for this minor body, consistent with those of the neutral group of the Centaurs, and concluded that due to its relatively short perihelion, the object may have undergone surface sublimation and interior recrystallization. Pinilla-Alonso et al. (2013) used photometry, spectroscopy and numerical simulations to show that

²<http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm>

³http://ssd.jpl.nasa.gov/?planet_pos

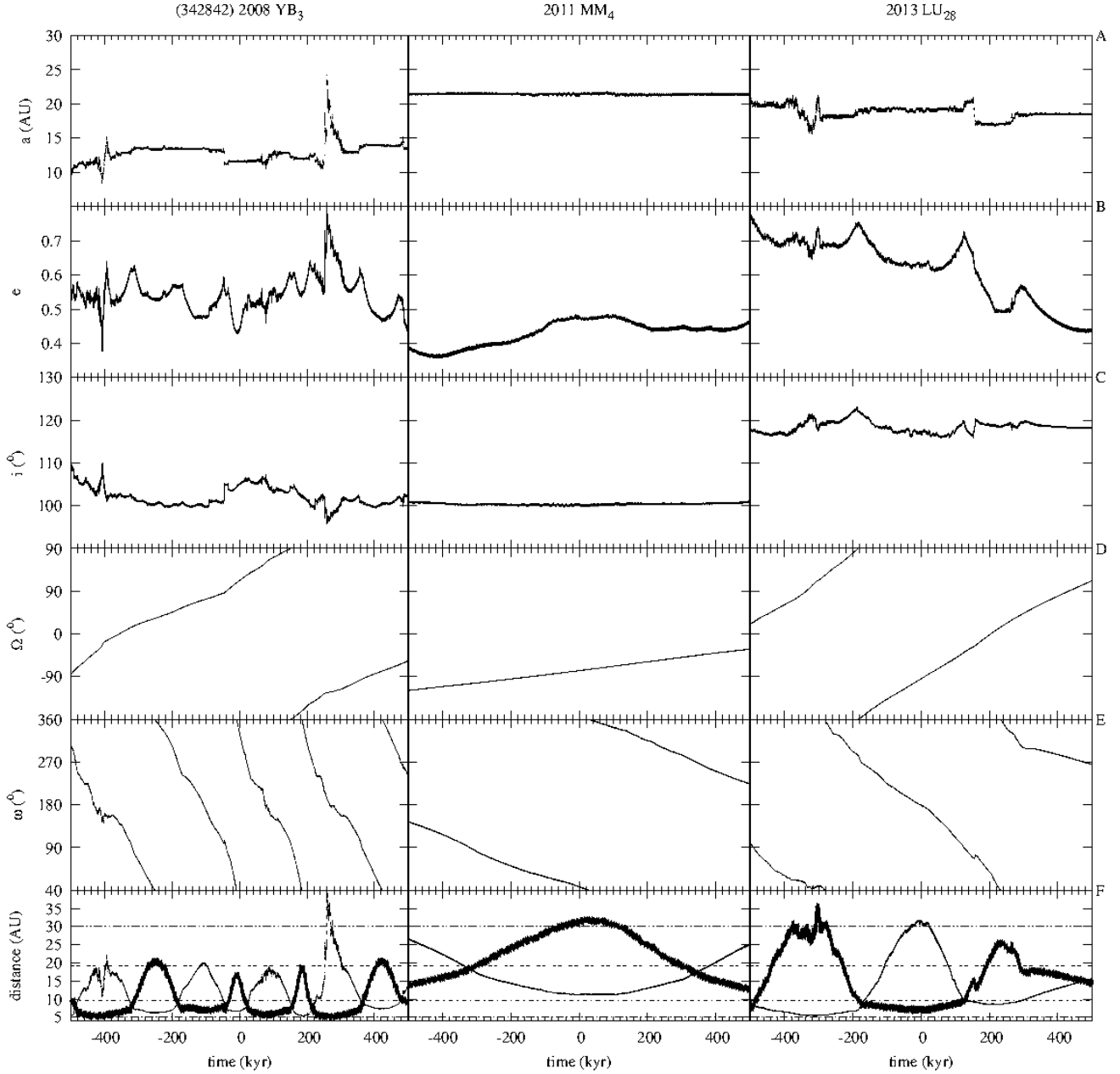


Fig. 6 Comparative time evolution of various parameters for the three largest retrograde Centaurs: (342842) 2008 YB₃ (left), 2011 MM₄ (centre) and 2013 LU₂₈ (right). The orbital elements a (panel A), e (panel B), i (panel C), Ω (panel D) and ω (panel E). The distances to the ascending (thick line) and descending nodes (dotted line) appear in panel F. The semi-major axes of the giant planets are also shown. The output time-step for these plots is 2 yr. These results correspond to the nominal orbits in Table 1.

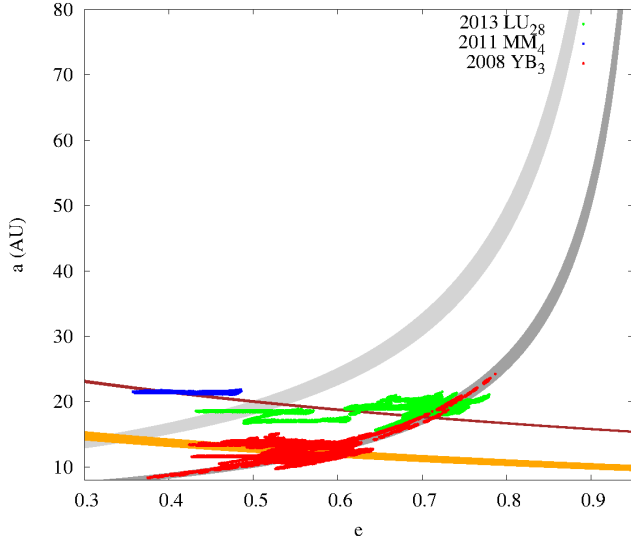


Fig. 4 Orbital evolution of (342842) 2008 YB₃, 2011 MM₄ and 2013 LU₂₈ in the time interval (-500, 500) kyr. Relatively long episodes of horizontal (resonant) oscillations are visible. For 2011 MM₄, no large changes in the orbital elements are observed over the studied time interval. The dark gray area represents the (e, a) combination with periapsis between the perihelion and aphelion of Jupiter, the light gray area shows the equivalent parameter domain if Saturn is considered instead of Jupiter. The orange area corresponds to the (e, a) combination with apoapsis between the perihelion and aphelion of Uranus and the brown area shows that of Neptune. These results correspond to the nominal orbits in Table 1.

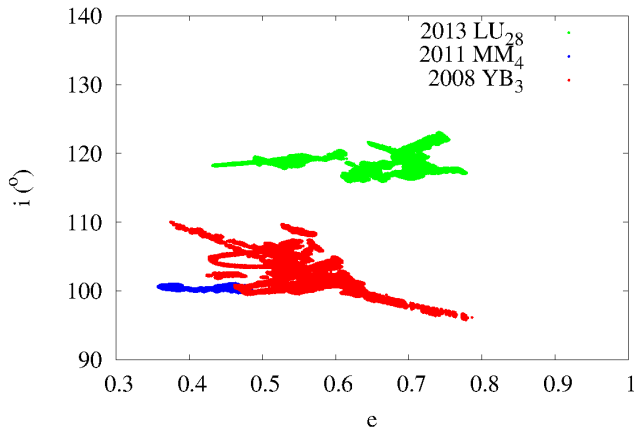


Fig. 5 Similar to Fig. 4 but for the (e, i) evolution.

this asteroid has a rotational period of 16.4 hr and, when compared with solar colours, is moderately red with low albedo (perhaps depleted of ices), and it came from the trans-Neptunian region.

Asteroid 342842 is currently trapped in an accidental 3:10 retrograde resonance with Jupiter (libration around 0° , see Fig. 7, top panel). We call it accidental because the resonant argument circulates with a superimposed short-period oscillation. This behaviour is similar to the one found for Plutino (15810) 1994 JR₁, a quasi-satellite of Pluto (de la Fuente Marcos and de la Fuente Marcos 2012b). This resonant episode with Jupiter started nearly 30 kyr ago and it will cease in about 10 kyr. Just after the episode, this minor body will be submitted to a 3:4 retrograde resonance with Saturn (asymmetric libration around 0° , see Fig. 7, bottom panel) for nearly 10 kyr. Close encounters with Jupiter and more distant flybys with Saturn trigger the ejection from the retrograde resonances with Jupiter and Saturn. All the control orbits exhibit similar behaviour during the time-span plotted in Fig. 7 but the dynamical evolution after the close encounters differs significantly between control orbits. In about half the cases, the 3:4 retrograde resonance with Saturn is observed prior and after the 3:10 retrograde resonance with Jupiter. The time-scale necessary for two initially infinitesimally close trajectories associated with this object to separate appreciably, or e -folding time, is ~ 3 kyr. The object will be ejected towards the trans-Neptunian region within the next few hundred kyr. Our results indicate that this object is less dynamically stable than implied in Pinilla-Alonso et al. (2013).

3.2 2011 MM₄

Asteroid 2011 MM₄ was discovered on 2011 June 24 by N. Primak, A. Schultz, S. Watters, J. Thiel and T. Goggia observing for the Pan-STARRS 1 project with the 1.8-m Ritchey-Chretien telescope from Haleakala (Woodworth et al. 2011). When discovered, its r magnitude was 21.1. It follows a path characterized by $a = 21.21$ AU, $e = 0.47$ and $i = 100^\circ$ (see Table 1). Its orbit is relatively well determined with 92 observations spanning a data-arc of 396 d. With $H = 9.3$ mag, it is very similar in size to (342842) 2008 YB₃ although probably larger (Bauer et al. 2013).

Asteroid 2011 MM₄ is currently trapped in the 3:10 retrograde resonance with Saturn (asymmetric libration around 90° , see Fig. 8, top panel). This resonant episode started nearly 14 kyr ago and it will end in about 3 kyr. Prior to this episode, we observe that the critical angle alternates between circulation and asymmetric libration, indicating that the motion is chaotic.

Before and after the resonant interaction with Saturn, this minor body was submitted to the 5:3 retrograde resonance with Neptune (asymmetric libration around 180° , see Fig. 8, bottom panel). Relatively close encounters with Saturn and Neptune are responsible for the ejection from the resonances. During the entire resonant phase, the argument of perihelion remains close to 0° , suggesting a behaviour similar to that of a Kozai secular resonance (Kozai 1962) although both e and i remain relatively constant (see Fig. 6). As in the previous case, all the control orbits exhibit similar behaviour during the time-span plotted in Fig. 8. In some cases, the 3:10 retrograde resonance with Saturn results in asymmetric libration around 180° instead of 90° .

Our integrations indicate that this object can remain dynamically stable for several Myr although this issue will be studied in more detail later. Its e -folding time is ~ 10 kyr though. It is not submitted to any typical secular resonance (see Fig. 9). The cause of the relative stability of this object in comparison with the others, is connected with the position of its nodes (see Fig. 6, panel F, middle column). For a minor body moving in a near-polar orbit, close encounters with major planets are only possible in the vicinity of the nodes. When ω is close to 0° or 180° , the perihelion takes place within the ecliptic plane with one node situated at aphelion and the other at perihelion; however, if ω is close to 90° or 270° , the perihelion occurs well away from the plane. In the case of 2011 MM₄, when ω is 0° or 180° , encounters with Saturn and Neptune take place at perihelion and aphelion; if ω is 90° or 270° , encounters with Uranus are possible at both nodes in a manner similar to what is observed for 83982 Crantor (2002 GO₉), a well-studied Uranian co-orbital (de la Fuente Marcos and de la Fuente Marcos 2013). The period of this oscillation of the nodes is nearly 700 kyr. At present time, the closest approach to Saturn is at 1.08 AU but the Hill radius of Saturn is 0.41 AU; for Neptune, the closest approach is at 0.94 AU but its Hill radius is 0.77 AU. This explains why its motion is rather stable, the planetary perturbations exerted on 2011 MM₄ are currently not strong enough to change the orbit appreciably.

3.3 2013 LU₂₈

Asteroid 2013 LU₂₈ was discovered on 2013 June 8 by A. Boattini, R. E. Hill and J. A. Johnson observing with the 1.5-m telescope of the Mt. Lemmon Survey (Bressi et al. 2013). It had a V magnitude of 21.7 when first observed. Its orbit is very poorly determined with just 27 observations acquired during 7 d and it is mainly included here to encourage follow-up observations. Its orbit is, in principle, the most eccentric of the ones

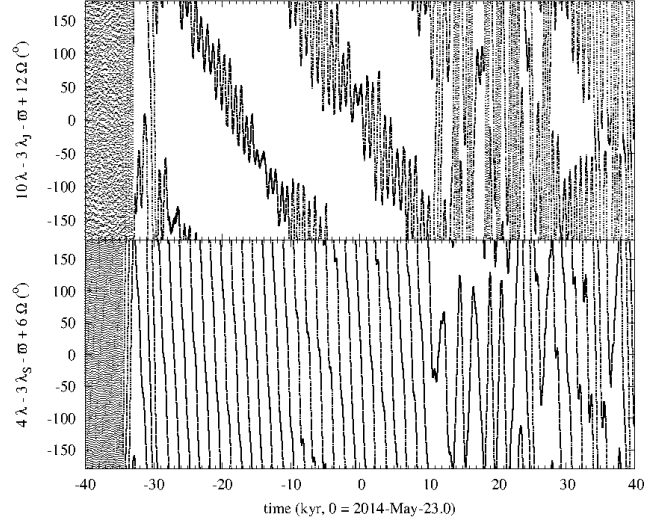


Fig. 7 Evolution of resonant arguments for (342842) 2008 YB₃.

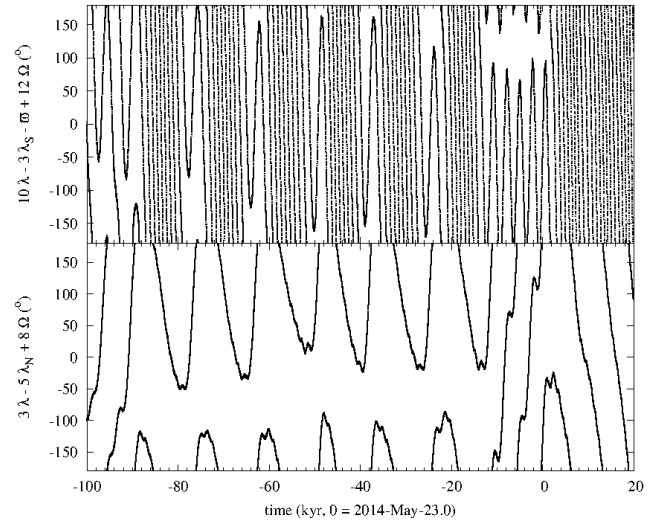


Fig. 8 Evolution of resonant arguments for 2011 MM₄.

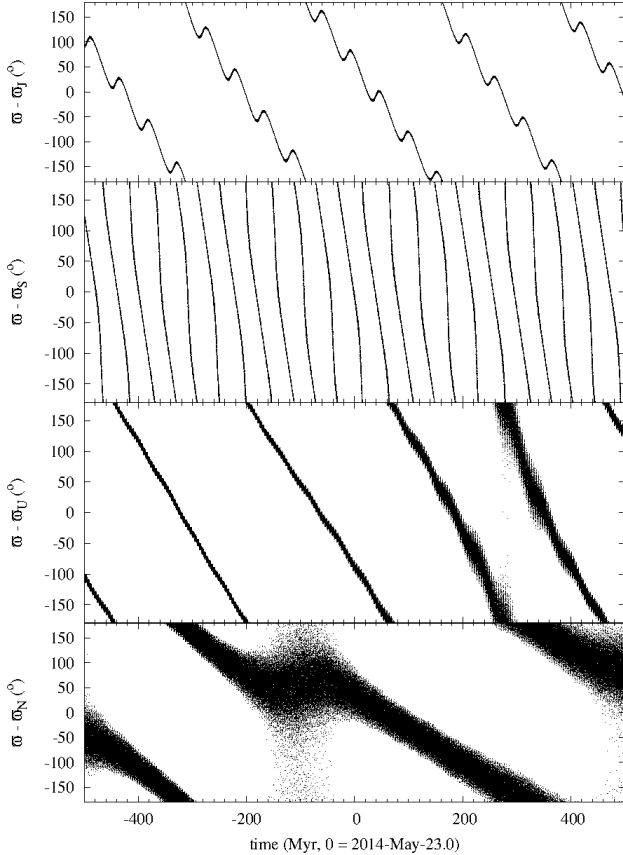


Fig. 9 Time evolution of the relative longitude of the perihelion, $\Delta\varpi$, of 2011 MM₄ with respect to the giant planets: referred to Jupiter ($\varpi - \varpi_J$), to Saturn ($\varpi - \varpi_S$), to Uranus ($\varpi - \varpi_U$), and to Neptune ($\varpi - \varpi_N$). In all cases, the resonant argument $\Delta\varpi$ circulates over the entire simulated time interval although it is nearly in secular resonance with Jupiter. These results are for the nominal orbit in Table 1.

discussed here. This object is also the largest, with $H = 8.1$ mag or 50–150 km.

Due to the large uncertainty associated to the orbit of 2013 LU₂₈, our discussion here is more speculative. Assuming an object moving in an orbit like the nominal one ($a = 19.25$ AU, $e = 0.63$, $i = 117^\circ 00$, $\Omega = 254^\circ 57$, $\omega = 179^\circ 05$ and $M = 297^\circ 87$), we observe that it is trapped in the 1:1 retrograde resonance with Uranus (asymmetric quasi-satellite behaviour, see Fig. 10, middle panel). The object has remained in the neighbourhood of this resonance for nearly 200 kyr but its dynamical status is rather unstable because it is submitted to additional resonances with Neptune and Saturn (see Fig. 10, bottom and top panels), 2:1 and 4:11 retrograde, respectively. Our results are consistent with previous studies of the 1:1 resonance at high inclination (see e.g. Brasser et al. 2004). All the control orbits suggest that it is a recent visitor from the trans-Neptunian region. In this case, and given its very uncertain parameters, we have restricted our exploration of the orbital domain to orbits very close to the nominal one. Its e -folding time is ~ 3 kyr.

4 Discussion

The distribution in absolute magnitude of known retrograde Centaurs with semi-major axis in the range 6–34 AU exhibits a clear deficit of objects within 10–14 mag and a significant excess at ~ 14 mag. This is consistent with theoretical expectations based on collisional models (Fraser 2009). Objects with $H < 10$ mag form a distinct group in dynamical terms.

The largest known retrograde Centaurs move in near-polar, comet-like orbits but no cometary activity has been detected yet on any of them. The analysis of the short-term orbital evolution of these objects shows that the group is heterogeneous in origin. All of them are currently trapped in transient retrograde resonances with the Jovian planets. Compared with the objects analysed by Morais and Namouni (2013b), the duration of the resonant episodes of the objects studied here is longer as they are globally more stable. Asteroid (342842) 2008 YB₃ will escape towards the trans-Neptunian region in the near future and 2013 LU₂₈, a recent visitor from the trans-Neptunian region, is the first known Uranian retrograde co-orbital candidate (a quasi-satellite) but further observations are necessary to absolutely confirm that this object is indeed a retrograde companion to Uranus.

Another interesting feature of the dynamics discussed above is that high-order resonances seem to be preferred by these initial conditions characterized by

very high inclinations. This is, however, not surprising as pointed out by, for example, Robutel and Laskar (2001) or Gallardo (2006). The strength of high-order resonances in general is greater for high-inclination orbits. At high inclination, high-order resonances are strong enough to capture objects for relatively long periods of time. In our case, the high eccentricities are also a contributing factor to produce stronger dynamical effects (see e.g. Gallardo 2006). Gallardo (2006) has found that, for a given eccentricity and due to short-period planetary perturbations, high-inclination resonant orbits have a higher probability of survival than low-inclination ones. This is also consistent with the comparatively weaker stability observed for the retrograde resonances analysed by Morais and Namouni (2013b) and pointed out above; the orbits followed by the objects studied in their paper are not almost perpendicular to the ecliptic as in our case and their resonances are low order. In general, chaotic diffusion is enhanced for high-inclination, high-eccentricity orbits submitted to high-order resonances.

Asteroids 342842 and 2013 LU₂₈ are not long-term stable but 2011 MM₄ may be considerably more stable. In order to study the long-term stability of 2011 MM₄ we use the Regularized Mixed Variable Symplectic (RMVS) integrator (*swift-rmvs3*) which is part of the SWIFT package (Levison and Duncan 1994). The SWIFT package is available from H. Levison web site.⁴ The physical model here is similar to the one described in Sect. 3 but now the Earth and the Moon are replaced by the barycentre of the system. The calculations do not consider Mercury or any asteroids but they include the barycentre of the Pluto-Charon system, use a timestep of 50 d and run for ± 5.0 Gyr. Relative errors in the total energy are $< 4.0 \times 10^{-8}$. An ejection distance of 10000 AU from the Sun was used; any test particle that reached that distance was removed from the calculations. As in the previous simulations, we have followed the evolution of 50 control orbits obtained from the nominal orbital elements of 2011 MM₄ and their quoted uncertainties (see Table 1). These orbital elements have been sampled within 3σ from a six-dimensional Gaussian distribution around the nominal ones. Results from RMVS and Hermite are consistent within the applicable timeframe.

Horner et al. (2004a, 2004b) studied the dynamical half-lives of prograde Centaurs and found values in the range 0.54–32 Myr. The mean half-life of their sample of Centaurs was 2.7 Myr. For a given orbit, a large number of control orbits, N_o , with parameters close to those of the nominal one were integrated. These orbits

were followed until they resulted in a collision with the Sun or the ejection of the test particle from the Solar System. The number of control orbits, N , that still remain within the boundaries of the Solar System (in our case, within 10000 AU from the Sun) after a time t , is given by $N = N_o e^{-\lambda t}$, where $\lambda = 0.693/T_{1/2}$, λ is the decay constant and $T_{1/2}$ is the dynamical half-life of the objects.

Using *swift-rmvs3*, we have applied the same approach to 2011 MM₄ in an attempt to study its long-term stability. Asteroid 2011 MM₄ is clearly far more dynamically stable than most Centaurs; its mean dynamical half-life is 23.12 Myr. However, the range in dynamical half-lives forward in time is 5.26–310.32 Myr and for the past injection into its present orbit is 3.56–1795.35 Myr. In other words, this object probably arrived to the region of the giant planets nearly 23 Myr ago and certainly not earlier than nearly 2 Gyr ago. Therefore, it is not a primordial minor body that has remained around its present location since the formation of the Solar System like Jovian or Martian Trojans. It will be ejected also within 23 Myr and not later than 310 Myr into the future.

Among the control orbits, we have found one that is particularly interesting ($a = 21.1623$ AU, $e = 0.47301$, $i = 100.446^\circ$, $\Omega = 282.604^\circ$ and $\omega = 7.224^\circ$, see Fig. 11). It was very long lived into the past (1795.35 Myr) and its associated dynamics may signal the presence of a reservoir of asteroids moving in high-inclination prograde orbits that are submitted to a Kozai resonance as described by Gallardo (2006). In Fig. 11, the control orbit begins at a critical inclination of $\sim 63^\circ$ and very high eccentricity. From there, the eccentricity decreases and the initially prograde orbit turns into a retrograde one. If, somehow, a reservoir of objects moving with orbital inclinations $\sim 63^\circ$ and high eccentricities was created (and may still survive) at 200–500 AU in the remote past, it may be a viable secondary source for retrograde Centaurs.

The dynamical evolutionary pathway uncovered by our calculations, even if it has a statistically low probability, shows that the Oort cloud is not the only possible source region for retrograde Centaurs. The existence of additional stable reservoirs of rocky and icy bodies at 100–300 AU cannot be simply casted aside. This interpretation is, however, tentative and should be treated with caution, as there is recent circumstantial evidence on the existence of a massive planet at 250 AU from the Sun (Trujillo and Sheppard 2014). If such planet does indeed exist, the architecture of the entire trans-Plutonian region could be very different from the one assumed here, i.e. no truly massive bodies beyond Neptune. A massive perturber in the region 100–300 AU

⁴<http://www.boulder.swri.edu/~hal/swift.html>

may affect the dynamical evolution presented in Figure 11 very significantly.

Brasser et al. (2012), and Volk and Malhotra (2013) argued that retrograde or very high inclination Centaurs have their origin in the Oort cloud. Fouchard et al. (2014) also pointed out that the Oort cloud, and in particular its inner part, is a potential source of high inclination Centaurs. Long-period comets are believed to have their origin in the Oort cloud (see e.g. Duncan 2008). Halley-type comets may come from the outer edge of the scattered disc (Levison et al. 2006) or the Oort cloud (Emel'yanenko et al. 2013). Jupiter-family comets appear to have their origin in the scattered disc (Levison and Duncan 1997). For the group of minor bodies whose semi-major axes are between 6 and 34 AU, the fraction of retrograde orbits is 11.3%. There are 165 known comets with semi-major axes in the range 6–34 AU. Out of them, 20 objects or 12.1% move in retrograde orbits. The fractions of retrograde orbits in both groups are more similar than expected by chance alone. In principle, this fact argues strongly in favour of a dominant source in the Oort cloud for the retrograde Centaurs but, again, the possible existence of trans-Plutonian planets may change the entire dynamical scenario.

Asteroid 2011 MM₄ is a promising candidate to be a representative of a remnant population of primordial planetesimals and it is a good candidate to be submitted to the nodal libration mechanism (Verrier and Evans 2008, 2009; Farago and Laskar 2010; Doolin and Blundell 2011), at least temporarily. This mechanism, when active, can significantly enhance the stability of near-polar orbits. Minor bodies like 2011 MM₄ may signal the size threshold for catastrophic collisions in the early Solar System. Returning to the issue of its origin, and as alternative to the Oort cloud or the hypothetical high-inclination reservoir pointed out above, we speculate that this and other similar objects may be ancient ejected Uranian satellites (regular or irregular). The Uranian satellite system is the least massive among those of the Jovian planets even if the largest one, Titania, is the eighth largest moon in the Solar System. Uranus rotates nearly on its side with the axis lying nearly in its orbital plane. Uranus' large moons follow regular paths in equatorial-plane orbits. Any object originally bound to Uranus and tracing an orbit lying nearly in its equatorial plane will follow an almost polar orbit when ejected.

5 Conclusions

In this research, we have used a comparative statistical analysis of the properties of known prograde and retrograde Centaurs to reveal compelling reasons to single

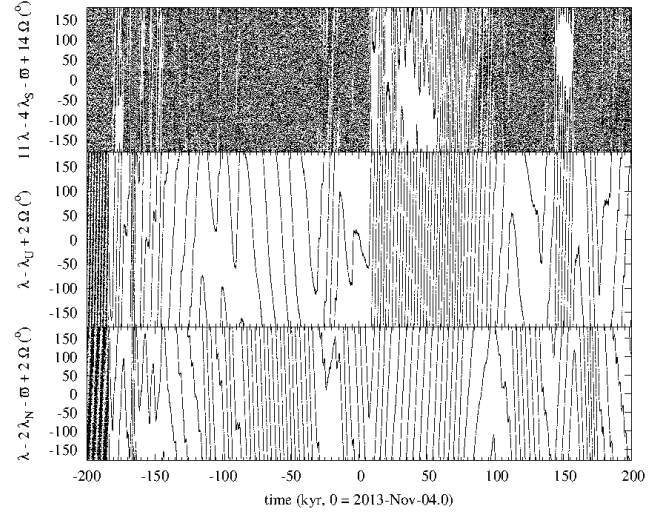


Fig. 10 Evolution of resonant arguments for 2013 LU₂₈.

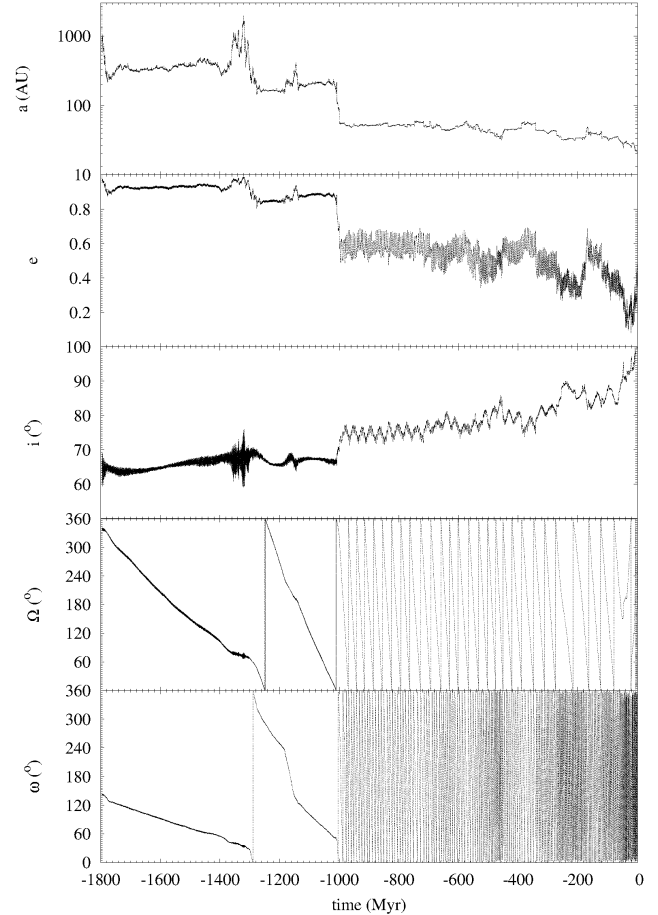


Fig. 11 Time evolution of one of the control orbits of 2011 MM₄: semi-major axis, a , eccentricity, e , inclination, i , longitude of the perihelion, Ω , and, argument of perihelion, ω . The output time-step for this plot is 0.045 Myr. These results correspond to the control orbit defined by $a = 21.1623$ AU, $e = 0.47301$, $i = 100.446^\circ$, $\Omega = 282.604^\circ$ and $\omega = 7.224^\circ$.

out the largest retrograde objects. The dynamical evolution of these objects has been subsequently studied using N -body simulations. The main conclusions of our work can be summarized as follows:

- The distribution in absolute magnitude of known retrograde Centaurs with semi-major axis in the range 6–34 AU exhibits a clear deficit of objects in the range 10–14 mag and a significant excess at ~ 14 mag.
- The largest retrograde Centaurs move in almost polar, very eccentric paths with their nodal points currently located near perihelion and aphelion. Within the retrograde Centaur population, they are clear outliers both in terms of dynamics and size.
- The largest retrograde Centaurs are currently trapped in transient retrograde, mostly high-order, resonances with the Jovian planets. These resonances are strong enough to induce substantial chaotic diffusion and make their orbits dynamically unstable.
- Asteroid (342842) 2008 YB₃ appears to be significantly less dynamically stable than usually assumed.
- Asteroid 2011 MM₄ may be a visitor from the Oort cloud but an origin in a relatively stable closer reservoir cannot be ruled out.
- Asteroid 2013 LU₂₈ is the first known Uranian retrograde co-orbital candidate (a quasi-satellite).
- This population may have its origin in the Oort cloud but alternative or concurrent sources could be ancient ejected Uranian satellites or a hypothetical reservoir of minor bodies moving in high-inclination, high-eccentricity orbits at 200–500 AU and submitted to the Kozai resonance.

Our dynamical analysis has been restricted to just three objects and their associated orbital parameter space. However, a number of distinctive properties that should be common to any retrograde Centaurs have been identified. In particular, the role of high-order resonances at high inclination as anticipated by Gallardo (2006) seems to be determinant on the short-term evolution of this population.

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